

## **TITLE OF THE INVENTION**

LDPC (Low Density Parity Check) coded modulation symbol decoding

## **CROSS REFERENCE TO RELATED PATENTS/PATENT APPLICATIONS**

5 The present U.S. Utility Patent Application claims priority pursuant to 35 U.S.C. § 119(e) to the following U.S. Provisional Patent Applications which are hereby incorporated herein by reference in their entirety and made part of the present U.S. Utility Patent Application for all purposes:

1. U.S. Provisional Patent Application Serial No. 60/384,698, entitled "Variable code rate and signal constellation turbo trellis coded modulation codec,"  
10 (Attorney Docket No. BP 2333), filed May 31, 2002 (05/31/2002), pending.

2. U.S. Provisional Application Serial No. 60/478,690, "Coded modulation with LDPC (Low Density Parity Check) code using variable maps and metric updating," (Attorney Docket No. BP3036), filed June 13, 2003 (06/13/2003), pending.

3. U.S. Provisional Application Serial No. 60/490,967, "LDPC (Low  
15 Density Parity Check) coded modulation symbol decoding," (Attorney Docket No. BP3089), filed July 29, 2003 (07/29/2003), pending.

The present U.S. Utility Patent Application also claims priority pursuant to 35 U.S.C. § 120 to the following U.S. Utility Patent Application which is hereby incorporated herein by reference in its entirety and made part of the present U.S.  
20 Utility Patent Application for all purposes:

1. U.S. Utility Application Serial No. 10/264,486, entitled "Variable code rate and signal constellation turbo trellis coded modulation codec," (Attorney Docket No. BP 2333), filed October 4, 2002 (10/04/2002), pending, which claims priority pursuant to 35 U.S.C. § 119(e) to U.S. Provisional Patent Application Serial No.  
25 60/384,698, entitled "Variable code rate and signal constellation turbo trellis coded modulation codec," (Attorney Docket No. BP 2333), filed May 31, 2002 (05/31/2002), pending.

## **BACKGROUND OF THE INVENTION**

## **TECHNICAL FIELD OF THE INVENTION**

30 The invention relates generally to communication systems; and, more particularly, it relates to decoding of signals within such communication systems.

## DESCRIPTION OF RELATED ART

Data communication systems have been under continual development for many years. One such type of communication system that has been of significant interest lately is a communication system that employs turbo codes. Another type of communication system that has also received interest is a communication system that employs LDPC (Low Density Parity Check) code d modulation. A primary directive in these areas of development has been to try continually to lower the error floor within a communication system. The ideal goal has been to try to reach Shannon's limit in a communication channel. Shannon's limit may be viewed as being the data rate to be used in a communication channel, having a particular SNR (Signal to Noise Ratio), that achieves error free transmission through the communication channel. In other words, the Shannon limit is the theoretical bound for channel capacity for a given modulation and code rate.

LDPC code has been shown to provide for excellent decoding performance that can approach the Shannon limit in some cases. For example, some LDPC decoders have been shown to come within 0.3 dB (decibels) from the theoretical Shannon limit. While this example was achieved using an irregular LDPC code of a length of one million, it nevertheless demonstrates the very promising application of LDPC codes within communication systems.

Typical decoding of LDPC coded modulation signals is performed based on a bipartite graph of a given LDPC code such that the graph includes bit nodes and check nodes. The I,Q (In-phase, Quadrature) values associated with received symbols are associated with a symbol node, and that symbol node is associated with corresponding bit nodes. Bit metrics are then calculated for the individual bits of the corresponding symbols, and those bit metrics are provided to the bit nodes of the bipartite graph of the given LDPC code. Edge information corresponding to the edges that interconnect the bit nodes and the check nodes is calculated, and appropriately updated, and communicated back and forth between the bit nodes and the check nodes during iterative decoding of the LDPC coded signal. Therefore, such LDPC decoding is typically performed with respect to the bit nodes and the check nodes of the LDPC bipartite graph. One disadvantage of this approach to LDPC decoding is that it can be

very memory and processing resource consumptive. Even in instances where there are sufficient memory and processing resources available, the previous approaches to perform LDPC decoding typically do not give a sufficiently high level of performance for some applications. With the ever-improvements developments in memory  
5 management and processing resource allocation, a higher performance means by which LDPC coded modulation signals may be decoded would be desirable.

### BRIEF SUMMARY OF THE INVENTION

Various aspects of the invention can be found in any number of devices that perform LDPC (Low Density Parity Check) coded modulation symbol decoding. That is to say, the decoding is performed on a symbol level basis whereas prior art LDPC decoding approaches all include performing the decoding on a bit level basis. An LDPC coded modulation tripartite graph may be appropriately modified to an LDPC coded modulation bipartite graph to facilitate this symbol level decoding of the LDPC coded modulation signal.

The symbols of signal received by a device that includes the invention may be arranged in a symbol block. The signal may be a variable code rate signal and/or a variable modulation signal whose code rate and/or modulation may vary as frequently as on a symbol by symbol basis. Moreover, a combination (or hybrid) decoding approach may also be performed in some other embodiments that include a combination of bit level decoding (that may include bit metric updating) and symbol level decoding of LDPC coded signals. In some instances, a single device (e.g., a transceiver or a receiver) is operable to perform the decoding using one or more of these approaches in accordance with invention.

One embodiment of the invention may be found in a decoder that is operable to perform symbol decoding of an LDPC coded modulation signal. In one instance, the decoder includes a check node update functional block and a symbol sequence estimate and symbol node update functional block. The check node update functional block calculates a plurality of forward metrics (alphas) and a plurality of backward metrics (betas) that correspond to each mapped symbol of a plurality of mapped symbols that is mapped from a plurality of symbols of the LDPC coded modulation signal. This calculation of the alphas and betas may be performed using a forward-backward technique throughout the symbol block.

The check node update functional block then uses the plurality of forward metrics and the plurality of backward metrics that correspond to each symbol of the plurality of symbols to update a plurality of edge messages that corresponds to a plurality of edges that communicatively couple a plurality of symbol nodes to a plurality of check nodes within an LDPC bipartite graph that corresponds to an LDPC

code. The symbol sequence estimate and symbol node update functional block computes a plurality of soft symbol estimates for each mapped symbol of the plurality of mapped symbols. The symbol sequence estimate and symbol node update functional block estimates each mapped symbol of the plurality of mapped symbols using the corresponding plurality of soft symbol estimates. The symbol sequence estimate and symbol node update functional block updates the plurality of edges using the estimates of each mapped symbol of the plurality of mapped symbols. The check node update functional block and the symbol sequence estimate and symbol node update functional block cooperatively perform iterative decoding in an effort to make final, best estimates of each symbol of the plurality of symbols within the LDPC coded modulation signal.

The LDPC coded modulation signal that is decoded by the decoder may be a variable modulation signal. In such instances, a first symbol of the plurality of symbols is mapped according to a first modulation that includes a first constellation and a corresponding first mapping, and a second symbol of the plurality of symbols is mapped according to a second modulation that includes a second constellation and a corresponding second mapping. That is to say, the various symbols of the LDPC coded modulation signal to be decoded may have different modulations such that different symbols may be mapped according to different constellation shapes having different mappings corresponding thereto.

Alternatively, the various symbols of the LDPC coded modulation signal to be decoded may be mapped according to a singular constellation shape wherein the various symbols having different mappings of the singular constellation shape. As an example, the first modulation may include an 8 PSK (8 Phase Shift Key) shaped constellation whose constellation points are mapped according to the first mapping, and the second modulation may include the same 8 PSK shaped constellation whose constellation points are mapped according to the second mapping (which is different than the first mapping).

The LDPC coded modulation signal that is decoded by the decoder may be a variable code rate signal. For example, a first symbol of the plurality of symbols is

encoded according to a first code rate, and a second symbol of the plurality of symbols is encoded according to a second code rate.

5 The various processing performed within the various functional blocks of the decoder may be performed using min\* processing. As some examples, the check node update functional block may calculate the plurality of forward metrics and the plurality of backward metrics that correspond to each symbol of the plurality of mapped symbols by employing min\* processing, and the symbol sequence estimate and symbol node update functional block may update the plurality of edges using the estimates of each mapped symbol of the plurality of mapped symbols by employing min\* processing.

10 Such a decoder built according to the invention may be implemented within a variety of types of communication devices that may be implemented within any number of types of communication systems. Some examples of such communications systems may include a satellite communications system, a HDTV (High Definition Television) communication system, a cellular communication system, a and microwave communication system, a point-to-point communication system, a uni-directional communication system, a bi-directional communication system, a one to many communication system, and a fiber optic communication system.

20 The invention envisions any type of communication devices that supports the functionality and/or processing described herein. Moreover, various types of methods may be performed to support the functionality described herein without departing from the scope and spirit of the invention.

**BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS**

FIG. 1 is a system diagram illustrating an embodiment of a satellite communication system that is built according to the invention.

FIG. 2 is a system diagram illustrating an embodiment of an HDTV (High Definition Television) communication system that is built according to the invention.

FIG. 3A and FIG. 3B are system diagrams illustrating embodiment of uni-directional cellular communication systems that are built according to the invention.

FIG. 4 is a system diagram illustrating an embodiment of a bi-directional cellular communication system that is built according to the invention.

FIG. 5 is a system diagram illustrating an embodiment of a uni-directional microwave communication system that is built according to the invention.

FIG. 6 is a system diagram illustrating an embodiment of a bi-directional microwave communication system that is built according to the invention.

FIG. 7 is a system diagram illustrating an embodiment of a uni-directional point-to-point radio communication system that is built according to the invention.

FIG. 8 is a system diagram illustrating an embodiment of a bi-directional point-to-point radio communication system that is built according to the invention.

FIG. 9 is a system diagram illustrating an embodiment of a uni-directional communication system that is built according to the invention.

FIG. 10 is a system diagram illustrating an embodiment of a bi-directional communication system that is built according to the invention.

FIG. 11 is a system diagram illustrating an embodiment of a one to many communication system that is built according to the invention.

FIG. 12 is a diagram illustrating an embodiment of a WLAN (Wireless Local Area Network) that may be implemented according to the invention.

FIG. 13 is a diagram illustrating an embodiment of a DSL (Digital Subscriber Line) communication system that may be implemented according to the invention.

FIG. 14 is a system diagram illustrating an embodiment of a fiber-optic communication system that is built according to the invention.

FIG. 15 is a system diagram illustrating an embodiment of a satellite receiver STB (Set Top Box) system that is built according to the invention.

FIG. 16 is a diagram illustrating an embodiment of an LDPC (Low Density Parity Check) code bipartite graph.

FIG. 17A is a diagram illustrating an embodiment of direct combining of LDPC (Low Density Parity Check) coding and modulation encoding.

5        FIG. 17B is a diagram illustrating an embodiment of BICM (Bit Interleaved Coded Modulation) that is employed in conjunction with LDPC (Low Density Parity Check) coding and modulation encoding.

FIG. 17C is a diagram illustrating an embodiment of multilevel coded modulation encoding.

10       FIG. 18 is a diagram illustrating an embodiment of a variable signal mapping LDPC (Low Density Parity Check) coded modulation system that is built in accordance with invention.

FIG. 19 is a diagram illustrating an embodiment of LDPC (Low Density Parity Check) coded modulation decoding functionality using bit metric according to the  
15       invention.

FIG. 20 is a diagram illustrating an alternative embodiment of LDPC coded modulation decoding functionality using bit metric according to the invention (when performing n number of iterations).

FIG. 21 is a diagram illustrating an alternative embodiment of LDPC (Low  
20       Density Parity Check) coded modulation decoding functionality using bit metric (with bit metric updating) according to the invention.

FIG. 22 is a diagram illustrating an alternative embodiment of LDPC coded modulation decoding functionality using bit metric (with bit metric updating) according to the invention (when performing n number of iterations).

25       FIG. 23A is a diagram illustrating bit decoding using bit metric (shown with respect to an LDPC (Low Density Parity Check) code bipartite graph) according to the invention.

FIG. 23B is a diagram illustrating bit decoding using bit metric updating (shown with respect to an LDPC (Low Density Parity Check) code bipartite graph)  
30       according to the invention.



FIG. 24A is a diagram illustrating an LDPC (Low Density Parity Check) coded modulation tripartite graph with symbol nodes connected to bit nodes according to the invention.

5 FIG. 24B is a diagram illustrating an LDPC (Low Density Parity Check) coded modulation bipartite graph with symbol nodes connected directly to check nodes according to the invention (this bipartite graph is generated from the tripartite graph shown in FIG. 24A).

10 FIG. 25A is a diagram illustrating symbol decoding (shown with respect to an LDPC (Low Density Parity Check) coded modulation bipartite graph) according to the invention.

FIG. 25B is a diagram illustrating an embodiment of symbol decoding functionality (supported with an LDPC (Low Density Parity Check) coded modulation bipartite graph) according to the invention.

15 FIG. 26 is a diagram illustrating an embodiment of performance comparison of symbol vs. bit decoding of LDPC (Low Density Parity Check) code modulation signals according to the invention.

FIG. 27 is a diagram illustrating an embodiment of hybrid decoding functionality that reduces the complexity of symbol decoding of LDPC coded modulation signals according to the invention.

20 FIG. 28A is a flowchart illustrating an embodiment of a method for symbol decoding of LDPC coded modulation signals according to the invention.

FIG. 28B is a flowchart illustrating an embodiment of a hybrid decoding method of LDPC coded modulation signals according to the invention.

## DETAILED DESCRIPTION OF THE INVENTION

Various aspects of the invention may be found in any number of devices that perform symbol decoding of LDPC (Low Density Parity Check) coded signals. In some instances, the LDPC symbol decoding is performed on signals whose code rate and/or modulation may vary as frequently as on a symbol by symbol basis.

Various system embodiments are described below where any of the various aspects of the invention may be implemented. In general, any device that performs symbol decoding of LDPC coded signals may benefit from the invention.

FIG. 1 is a system diagram illustrating an embodiment of a satellite communication system that is built according to the invention. A satellite transmitter is communicatively coupled to a satellite dish that is operable to communicate with a satellite. The satellite transmitter may also be communicatively coupled to a wired network. This wired network may include any number of networks including the Internet, proprietary networks, other wired networks and/or WANs (Wide Area Networks). The satellite transmitter employs the satellite dish to communicate to the satellite via a wireless communication channel. The satellite is able to communicate with one or more satellite receivers (each having a satellite dish). Each of the satellite receivers may also be communicatively coupled to a display.

Here, the communication to and from the satellite may cooperatively be viewed as being a wireless communication channel, or each of the communication links to and from the satellite may be viewed as being two distinct wireless communication channels.

For example, the wireless communication “channel” may be viewed as not including multiple wireless hops in one embodiment. In other multi-hop embodiments, the satellite receives a signal received from the satellite transmitter (via its satellite dish), amplifies it, and relays it to satellite receiver (via its satellite dish); the satellite receiver may also be implemented using terrestrial receivers such as satellite receivers, satellite based telephones, and/or satellite based Internet receivers, among other receiver types. In the case where the satellite receives a signal received from the satellite transmitter (via its satellite dish), amplifies it, and relays it, the satellite may be viewed as being a “transponder;” this is a multi-hop embodiment. In

addition, other satellites may exist that perform both receiver and transmitter operations in cooperation with the satellite. In this case, each leg of an up-down transmission via the wireless communication channel would be considered separately.

In whichever embodiment, the satellite communicates with the satellite receiver. The satellite receiver may be viewed as being a mobile unit in certain embodiments (employing a local antenna); alternatively, the satellite receiver may be viewed as being a satellite earth station that may be communicatively coupled to a wired network in a similar manner in which the satellite transmitter may also be communicatively coupled to a wired network.

The satellite transmitter is operable to encode information (using an encoder) that is to be transmitted to the satellite receiver; the satellite receiver is operable to decode the transmitted signal (using a decoder). The encoder may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoders within the satellite receivers may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. This diagram shows just one of the many embodiments where one or more of the various aspects of the invention may be found.

FIG. 2 is a system diagram illustrating an embodiment of an HDTV (High Definition Television) communication system that is built according to the invention. An HDTV transmitter is communicatively coupled to a tower. The HDTV transmitter, using its tower, transmits a signal to a local tower dish via a wireless communication channel. The local tower dish may communicatively couple to an HDTV STB (Set Top Box) receiver via a coaxial cable. The HDTV STB receiver includes the functionality to receive the wireless transmitted signal that has been received by the local tower dish. This functionality may include any transformation and/or down-converting that may be needed to accommodate any up-converting that may have been

performed before and during transmission of the signal from the HDTV transmitter and its corresponding tower to transform the signal into a format that is compatible with the communication channel across which it is transmitted.

The HDTV STB receiver is also communicatively coupled to an HDTV display  
5 that is able to display the demodulated and decoded wireless transmitted signals received by the HDTV STB receiver and its local tower dish. The HDTV transmitter (via its tower) transmits a signal directly to the local tower dish via the wireless communication channel in this embodiment. In alternative embodiments, the HDTV transmitter may first receive a signal from a satellite, using a satellite earth station that  
10 is communicatively coupled to the HDTV transmitter, and then transmit this received signal to the local tower dish via the wireless communication channel. In this situation, the HDTV transmitter operates as a relaying element to transfer a signal originally provided by the satellite that is destined for the HDTV STB receiver. For example, another satellite earth station may first transmit a signal to the satellite from  
15 another location, and the satellite may relay this signal to the satellite earth station that is communicatively coupled to the HDTV transmitter. The HDTV transmitter performs receiver functionality and then transmits its received signal to the local tower dish.

In even other embodiments, the HDTV transmitter employs its satellite earth  
20 station to communicate to the satellite via a wireless communication channel. The satellite is able to communicate with a local satellite dish; the local satellite dish communicatively couples to the HDTV STB receiver via a coaxial cable. This path of transmission shows yet another communication path where the HDTV STB receiver may communicate with the HDTV transmitter.

25 In whichever embodiment and whichever signal path the HDTV transmitter employs to communicate with the HDTV STB receiver, the HDTV STB receiver is operable to receive communication transmissions from the HDTV transmitter.

The HDTV transmitter is operable to encode information (using an encoder) that is to be transmitted to the HDTV STB receiver; the HDTV STB receiver is  
30 operable to decode the transmitted signal (using a decoder).

As within other embodiments that employ an encoder and a decoder, the encoder may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoder may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. This diagram shows yet another embodiment where one or more of the various aspects of the invention may be found.

FIG. 3A and FIG. 3B are system diagrams illustrating embodiments of unidirectional cellular communication systems that are built according to the invention.

Referring to the FIG. 3A, a mobile transmitter includes a local antenna communicatively coupled thereto. The mobile transmitter may be any number of types of transmitters including a one way cellular telephone, a wireless pager unit, a mobile computer having transmit functionality, or any other type of mobile transmitter. The mobile transmitter transmits a signal, using its local antenna, to a cellular tower via a wireless communication channel. The cellular tower is communicatively coupled to a base station receiver; the receiving tower is operable to receive data transmission from the local antenna of the mobile transmitter that has been communicated via the wireless communication channel. The cellular tower communicatively couples the received signal to the base station receiver.

The mobile transmitter is operable to encode information (using an encoder) that is to be transmitted to the base station receiver; the base station receiver is operable to decode the transmitted signal (using a decoder).

As within other embodiments that employ an encoder and a decoder, the encoder may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoder may be implemented to perform decoding of

LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. This diagram shows yet another embodiment where one or more of the various aspects of the invention may be found.

Referring to the FIG. 3B, a base station transmitter includes a cellular tower communicatively coupled thereto. The base station transmitter, using its cellular tower, transmits a signal to a mobile receiver via a communication channel. The mobile receiver may be any number of types of receivers including a one-way cellular telephone, a wireless pager unit, a mobile computer having receiver functionality, or any other type of mobile receiver. The mobile receiver is communicatively coupled to a local antenna; the local antenna is operable to receive data transmission from the cellular tower of the base station transmitter that has been communicated via the wireless communication channel. The local antenna communicatively couples the received signal to the mobile receiver.

The base station transmitter is operable to encode information (using an encoder) that is to be transmitted to the mobile receiver; the mobile receiver is operable to decode the transmitted signal (using a decoder).

As within other embodiments that employ an encoder and a decoder, the encoder may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoder may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. This diagram shows yet another embodiment where one or more of the various aspects of the invention may be found.

FIG. 4 is a system diagram illustrating an embodiment of a bi-directional cellular communication system, built according to the invention, where the communication can go to and from the base station transceiver and to and from the mobile transceiver via the wireless communication channel.

5 Referring to the FIG. 4, a base station transceiver includes a cellular tower communicatively coupled thereto. The base station transceiver, using its cellular tower, transmits a signal to a mobile transceiver via a communication channel. The reverse communication operation may also be performed. The mobile transceiver is able to transmit a signal to the base station transceiver as well. The mobile transceiver  
10 may be any number of types of transceiver including a cellular telephone, a wireless pager unit, a mobile computer having transceiver functionality, or any other type of mobile transceiver. The mobile transceiver is communicatively coupled to a local antenna; the local antenna is operable to receive data transmission from the cellular tower of the base station transceiver that has been communicated via the wireless  
15 communication channel. The local antenna communicatively couples the received signal to the mobile transceiver.

The base station transceiver is operable to encode information (using its corresponding encoder) that is to be transmitted to the mobile transceiver; the mobile transceiver is operable to decode the transmitted signal (using its corresponding  
20 decoder). Similarly, mobile transceiver is operable to encode information (using its corresponding encoder) that is to be transmitted to the base station transceiver; the base station transceiver is operable to decode the transmitted signal (using its corresponding decoder).

As within other embodiments that employ an encoder and a decoder, the  
25 encoder of either of the base station transceiver or the mobile transceiver may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoder of either of the base station transceiver or the mobile  
30 transceiver may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative

decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. This diagram shows yet another embodiment where one or more of the various aspects of the invention may be found.

FIG. 5 is a system diagram illustrating an embodiment of a uni-directional microwave communication system that is built according to the invention. A microwave transmitter is communicatively coupled to a microwave tower. The microwave transmitter, using its microwave tower, transmits a signal to a microwave tower via a wireless communication channel. A microwave receiver is communicatively coupled to the microwave tower. The microwave tower is able to receive transmissions from the microwave tower that have been communicated via the wireless communication channel.

The microwave transmitter is operable to encode information (using an encoder) that is to be transmitted to the microwave receiver; the microwave receiver is operable to decode the transmitted signal (using a decoder).

As within other embodiments that employ an encoder and a decoder, the encoder may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoder may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. This diagram shows yet another embodiment where one or more of the various aspects of the invention may be found.

FIG. 6 is a system diagram illustrating an embodiment of a bi-directional microwave communication system that is built according to the invention. Within the FIG. 6, a first microwave transceiver is communicatively coupled to a first microwave tower. The first microwave transceiver, using the first microwave tower (the first



microwave transceiver's microwave tower), transmits a signal to a second microwave tower of a second microwave transceiver via a wireless communication channel. The second microwave transceiver is communicatively coupled to the second microwave tower (the second microwave transceiver's microwave tower). The second microwave tower is able to receive transmissions from the first microwave tower that have been communicated via the wireless communication channel. The reverse communication operation may also be performed using the first and second microwave transceivers.

Each of the microwave transceivers is operable to encode information (using an encoder) that is to be transmitted to the other microwave transceiver; each microwave transceiver is operable to decode the transmitted signal (using a decoder) that it receives. Each of the microwave transceivers includes an encoder and a decoder.

As within other embodiments that employ an encoder and a decoder, the encoder of either of the microwave transceivers may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoder of either of the microwave transceivers may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. This diagram shows yet another embodiment where one or more of the various aspects of the invention may be found.

FIG. 7 is a system diagram illustrating an embodiment of a uni-directional point-to-point radio communication system, built according to the invention, where the communication goes from a mobile unit transmitter to a mobile unit receiver via the wireless communication channel.

A mobile unit transmitter includes a local antenna communicatively coupled thereto. The mobile unit transmitter, using its local antenna, transmits a signal to a local antenna of a mobile unit receiver via a wireless communication channel.

The mobile unit transmitter is operable to encode information (using an encoder) that is to be transmitted to the mobile unit receiver; the mobile unit receiver is operable to decode the transmitted signal (using a decoder).

As within other embodiments that employ an encoder and a decoder, the encoder may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoder may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. This diagram shows yet another embodiment where one or more of the various aspects of the invention may be found.

FIG. 8 is a system diagram illustrating an embodiment of a bi-directional point-to-point radio communication system that is built according to the invention. A first mobile unit transceiver is communicatively coupled to a first local antenna. The first mobile unit transceiver, using the first local antenna (the first mobile unit transceiver's local antenna), transmits a signal to a second local antenna of a second mobile unit transceiver via a wireless communication channel. The second mobile unit transceiver is communicatively coupled to the second local antenna (the second mobile unit transceiver's local antenna). The second local antenna is able to receive transmissions from the first local antenna that have been communicated via the communication channel. The reverse communication operation may also be performed using the first and second mobile unit transceivers.

Each mobile unit transceiver is operable to encode information (using its corresponding encoder) that is to be transmitted to the other mobile unit transceiver; each mobile unit transceiver is operable to decode the transmitted signal (using its corresponding decoder) that it receives.

As within other embodiments that employ an encoder and a decoder, the encoder of either of the mobile unit transceivers may be implemented to perform

encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoder of either of the mobile unit transceivers may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. This diagram shows yet another embodiment where one or more of the various aspects of the invention may be found.

FIG. 9 is a system diagram illustrating an embodiment of a uni-directional communication system that is built according to the invention. A transmitter communicates to a receiver via a uni-directional communication channel. The uni-directional communication channel may be a wireline (or wired) communication channel or a wireless communication channel without departing from the scope and spirit of the invention. The wired media by which the uni-directional communication channel may be implemented are varied, including coaxial cable, fiber-optic cabling, and copper cabling, among other types of "wiring." Similarly, the wireless manners in which the uni-directional communication channel may be implemented are varied, including satellite communication, cellular communication, microwave communication, and radio communication, among other types of wireless communication.

The transmitter is operable to encode information (using an encoder) that is to be transmitted to the receiver; the receiver is operable to decode the transmitted signal (using a decoder).

As within other embodiments that employ an encoder and a decoder, the encoder may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoder may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol

decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. This diagram shows yet another  
5 embodiment where one or more of the various aspects of the invention may be found.

FIG. 10 is a system diagram illustrating an embodiment of a bi-directional communication system that is built according to the invention. A first transceiver is communicatively coupled to a second transceiver via a bi-directional communication channel. The bi-directional communication channel may be a wireline (or wired)  
10 communication channel or a wireless communication channel without departing from the scope and spirit of the invention. The wired media by which the bi-directional communication channel may be implemented are varied, including coaxial cable, fiber-optic cabling, and copper cabling, among other types of "wiring." Similarly, the wireless manners in which the bi-directional communication channel may be  
15 implemented are varied, including satellite communication, cellular communication, microwave communication, and radio communication, among other types of wireless communication.

Each of the transceivers is operable to encode information (using its corresponding encoder) that is to be transmitted to the other transceiver; each  
20 transceiver is operable to decode the transmitted signal (using its corresponding decoder) that it receives.

As within other embodiments that employ an encoder and a decoder, the encoder of either of the transceivers may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an  
25 LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoder of either of the transceivers may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to  
30 accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by

symbol basis. This diagram shows yet another embodiment where one or more of the various aspects of the invention may be found.

FIG. 11 is a system diagram illustrating an embodiment of a one to many communication system that is built according to the invention. A transmitter is able to communicate, via broadcast in certain embodiments, with a number of receivers, shown as receivers 1, ..., n via a uni-directional communication channel. The uni-directional communication channel may be a wireline (or wired) communication channel or a wireless communication channel without departing from the scope and spirit of the invention. The wired media by which the bi-directional communication channel may be implemented are varied, including coaxial cable, fiber-optic cabling, and copper cabling, among other types of "wiring." Similarly, the wireless manners in which the bi-directional communication channel may be implemented are varied, including satellite communication, cellular communication, microwave communication, and radio communication, among other types of wireless communication.

A distribution point is employed within the one to many communication system to provide the appropriate communication to the receivers 1, ..., and n. In certain embodiments, the receivers 1, ..., and n each receive the same communication and individually discern which portion of the total communication is intended for them.

The transmitter is operable to encode information (using an encoder) that is to be transmitted to the receivers 1, ..., and n; each of the receivers 1, ..., and n is operable to decode the transmitted signal (using a decoder).

As within other embodiments that employ an encoder and a decoder, the encoder may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoders of any of the receivers 1, ..., and n may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation

and mapping) may vary as frequently as on a symbol by symbol basis. This diagram shows yet another embodiment where one or more of the various aspects of the invention may be found.

FIG. 12 is a diagram illustrating an embodiment of a WLAN (Wireless Local Area Network) that may be implemented according to the invention. The WLAN communication system may be implemented to include a number of devices that are all operable to communicate with one another via the WLAN. For example, the various devices that each include the functionality to interface with the WLAN may include any 1 or more of a laptop computer, a television, a PC (Personal Computer), a pen computer (that may be viewed as being a PDA (Personal Digital Assistant) in some instances, a personal electronic planner, or similar device), a mobile unit (that may be viewed as being a telephone, a pager, or some other mobile WLAN operable device), and/or a stationary unit (that may be viewed as a device that typically resides in a single location within the WLAN). The antennae of the various WLAN interactive devices may be integrated into the corresponding devices without departing from the scope and spirit of the invention as well.

This illustrated group of devices that may interact with the WLAN is not intended to be an exhaustive list of device that may interact with a WLAN, and a generic device shown as a WLAN interactive device represents a generic device that includes the functionality in order to interactive with the WLAN itself and/or the other devices that are associated with the WLAN. Any one of these devices that associate with the WLAN may be viewed generically as being a WLAN interactive device without departing from the scope and spirit of the invention. Each of the devices and the WLAN interactive device may be viewed as being located at nodes of the WLAN.

It is also noted that the WLAN itself may also include functionality to allow interfacing with other networks as well. These external networks may generically be referred to as WANs (Wide Area Networks). For example, the WLAN may include an Internet I/F (interface) that allows for interfacing to the Internet itself. This Internet I/F may be viewed as being a base station device for the WLAN that allows any one of the WLAN interactive devices to access the Internet.

It is also noted that the WLAN may also include functionality to allow interfacing with other networks (e.g., other WANs) besides simply the Internet. For example, the WLAN may include a microwave tower I/F that allows for interfacing to a microwave tower thereby allowing communication with one or more microwave networks. Similar to the Internet I/F described above, the microwave tower I/F may be viewed as being a base station device for the WLAN that allows any one of the WLAN interactive devices to access the one or more microwave networks via the microwave tower.

Moreover, the WLAN may include a satellite earth station I/F that allows for interfacing to a satellite earth station thereby allowing communication with one or more satellite networks. The satellite earth station I/F may be viewed as being a base station device for the WLAN that allows any one of the WLAN interactive devices to access the one or more satellite networks via the satellite earth station I/F.

This finite listing of various network types that may interface to the WLAN is also not intended to be exhaustive. For example, any other network may communicatively couple to the WLAN via an appropriate I/F that includes the functionality for any one of the WLAN interactive devices to access the other network.

Any of the various WLAN interactive devices described within this embodiment may include an encoder and a decoder to allow bi-directional communication with the other WLAN interactive device and/or the WANs.

Again, as within other embodiments that employ an encoder and a decoder, any of the encoder of within the various devices may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoders of any of the various devices may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on

a symbol by symbol basis. This diagram shows yet another embodiment where one or more of the various aspects of the invention may be found.

In general, any one of the WLAN interactive devices may be characterized as being an IEEE (Institute of Electrical & Electronics Engineers) 802.11 operable  
5 device. For example, such an 802.11 operable device may be an 802.11a operable device, an 802.11b operable device, or an 802.11g operable device. The IEEE 802.11g specification extends the rates for packet transmission in the 2.4 GHz frequency band. This is achieved by allowing packets, also known as frames, of two distinct types to coexist in this band. Frames utilizing DSSS/CCK (Direct Sequence Spread Spectrum  
10 with Complementary Code Keying) have been specified for transmission in the 2.4 GHz band at rates up to 11 Mbps (Mega-bits per second) as part of the 802.11b standard. The 802.11a standard uses a different frame format with OFDM (Orthogonal Frequency Division Multiplexing) to transmit at rates up to 54 Mbps with carrier frequencies in the 5 GHz range. The 802.11g specification allows for such OFDM  
15 frames to coexist with DSSS/CCK frames at 2.4 GHz.

FIG. 13 is a diagram illustrating an embodiment of a DSL (Digital Subscriber Line) communication system that may be implemented according to the invention. The DSL communication system includes an interfacing to the Internet (or some other WAN). In this diagram, the Internet itself is shown, but other WANs may also be  
20 employed without departing from the scope and spirit of the invention. An ISP (Internet Service Provider) is operable to communicate data to and from the Internet. The ISP communicatively couples to a CO (Central Office) that is typically operated by a telephone service company. The CO may also allow provide telephone services to one or more subscribers. However, the CO may also be implemented to allow  
25 interfacing of Internet traffic to and from one or more users (whose interactive devices are shown as user devices). These user devices may be a wide variety of devices including desk-top computers, laptop computers, servers, and/or hand held devices without departing from the scope and spirit of the invention. Any of these user devices may be wired or wireless typed devices as well. Each of the user devices is operably  
30 coupled to the CO via a DSL modem. The DSL modem may also be communicatively



coupled to a multiple user access point or hub to allow more than one user device to access the Internet.

The CO and the various DSL modems may also be implemented to include an encoder and a decoder to allow bi-directional communication therein. For example, the CO is operable to encode and decode data when communicating to and from the various DSL modems and the ISP. Similarly, each of the various DSL modems is operable to encode and decode data when communicating to and from the CO and its respective one or more user devices.

Again, as within other embodiments that employ an encoder and a decoder, the encoder of any of the CO and the various DSL modems may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoder of any of the CO and the various DSL modem may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. This diagram shows yet another embodiment where one or more of the various aspects of the invention may be found.

FIG. 14 is a system diagram illustrating an embodiment of a fiber-optic communication system that is built according to the invention. The fiber-optic communication system may be implemented to support encoding and/or decoding of LDPC coded signals. In some instances, these LDPC coded signals include a code rate and/or modulation (constellation and mapping) that may vary as frequently as on a symbol by symbol basis. Moreover, the fiber-optic communication system may be implemented to support LDPC symbol decoding within the iterative decoding processing.

The fiber-optic communication system includes a DWDM (Dense Wavelength Division Multiplexing (within the context of fiber optic communications)) line card

that is interposed between a line side and a client side. DWDM is a technology that has gained increasing interest recently. From both technical and economic perspectives, the ability to provide potentially unlimited transmission capacity is the most obvious advantage of DWDM technology. The current investment already made  
5 within fiber-optic infrastructure can not only be preserved when using DWDM, but it may even be optimized by a factor of at least 32. As demands change, more capacity can be added, either by simple equipment upgrades or by increasing the number of wavelengths (lambdas) on the fiber-optic cabling itself, without expensive upgrades. Capacity can be obtained for the cost of the equipment, and existing fiber plant  
10 investment is retained. From the bandwidth perspective, some of the most compelling technical advantage of DWDM can be summarized as follows:

The transparency of DWDM: Because DWDM is a PHY (physical layer) architecture, it can transparently support both TDM (Time Division Multiplexing) and data formats such as ATM (Asynchronous Transfer Mode), Gigabit Ethernet, ESCON,  
15 and Fibre Channel with open interfaces over a common physical layer.

The scalability of DWDM: DWDM can leverage the abundance of dark fiber in many metropolitan area and enterprise networks to quickly meet demand for capacity on point-to-point links and on spans of existing SONET/SDH rings.

The dynamic provisioning capabilities of DWDM: the fast, simple, and  
20 dynamic provisioning of network connections give providers the ability to provide high-bandwidth services in days rather than months.

Fiber-optic interfacing is employed at each of the client and line sides of the DWDM line card. The DWDM line card includes a transport processor that includes functionality to support DWDM long haul transport, DWDM metro transport, next-  
25 generation SONET/SDH multiplexers, digital cross-connects, and fiber-optic terminators and test equipment. On the line side, the DWDM line card includes a transmitter, that is operable to perform electrical to optical conversion for interfacing to an optical medium, and a receiver, that is operable to perform optical to electrical conversion for interfacing from the optical medium. On the client side, the DWDM  
30 line card includes a 10G serial module that is operable to communicate with any other devices on the client side of the fiber-optic communication system using a fiber-optic

interface. Alternatively, the interface may be implemented using non-fiber-optic media, including copper cabling and/or some other type of interface medium.

The DWDM transport processor of the DWDM line card includes a decoder that is used to decode received signals from either one or both of the line and client  
5 sides and an encoder that is used to encode signals to be transmitted to either one or both of the line and client sides.

As within other embodiments that employ an encoder and a decoder, the encoder may be implemented to perform encoding using LDPC coded modulation, and the LDPC encoding may be performed to generate an LDPC coded signal whose code  
10 rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. The decoder may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding processing of an LDPC coded  
15 signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. This diagram shows yet another embodiment where one or more of the various aspects of the invention may be found.

FIG. 15 is a system diagram illustrating an embodiment of a satellite receiver STB (Set Top Box) system that is built according to the invention. The satellite  
20 receiver STB system includes an advanced modulation satellite receiver that is implemented in an all digital architecture. Moreover, the advanced modulation satellite receiver may be implemented within a single integrated circuit in some embodiments. The satellite receiver STB system includes a satellite tuner that receives a signal via the L-band. The satellite tuner extracts I,Q (in-phase and quadrature)  
25 components from a signal received from the L-band and provides them to the advanced modulation satellite receiver. The advanced modulation satellite receiver includes a decoder.

As within other embodiments that employ a decoder, the decoder may be implemented to perform decoding of LDPC coded signals. This LDPC decoding may  
30 be implemented to perform symbol decoding within the iterative decoding processing. In addition, this LDPC decoding may also be implemented to accommodate decoding

processing of an LDPC coded signal whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis.

The advanced modulation satellite receiver may be implemented to communicatively couple to an HDTV MPEG-2 (Motion Picture Expert Group) transport de-mux, audio/video decoder and display engine. The advanced modulation satellite receiver and the HDTV MPEG-2 transport de-mux, audio/video decoder and display engine communicatively couple to a host CPU (Central Processing Unit). The HDTV MPEG-2 transport de-mux, audio/video decoder and display engine also communicatively couples to a memory module and a conditional access functional block. The HDTV MPEG-2 transport de-mux, audio/video decoder and display engine provides HD (High Definition) video and audio output that may be provided to an HDTV display.

The advanced modulation satellite receiver may be implemented as a single-chip digital satellite receiver supporting the decoder that performs decoding of LDPC coded signals via symbol decoding according to the invention. The advanced modulation satellite receiver is operable to receive communication provided to it from a transmitter device that includes an encoder as well.

In addition, several of the following Figures describe particular embodiments that may be used to implement some of the various aspects of the LDPC symbol decoding according to the invention. It is also noted that the various aspects of LDPC symbol decoding described herein may also be extended to perform decoding of LDPC coded signals whose code rate and/or modulation (constellation and mapping) may vary as frequently as on a symbol by symbol basis. Several details of these various aspects are provided below.

FIG. 16 is a diagram illustrating an embodiment of an LDPC (Low Density Parity Check) code bipartite graph. An LDPC code may be viewed as being a code having a binary parity check matrix such that nearly all of the elements of the matrix have values of zeros. For example,  $H = (h_{i,j})_{M \times N}$  may be viewed as being a parity check matrix of an LDPC code with block length N. If every column of the matrix has  $d_v$  1's, and every row of the matrix has  $d_c$  1's, then this code is referred to as a  $(d_v, d_c)$  regular LDPC code. For example, a regular (4,72) LDPC code would be viewed as

being a code whose binary parity check matrix would have 4 1's in every column and 72 1's in every row. These regular LDPC codes were introduced in R. Gallager, *Low-Density Parity-Check Codes*, Cambridge, MA: MIT Press, 1963.

A regular LDPC code can be represented as a bipartite graph by its parity check matrix with left side nodes representing variable of the code bits, and the right side nodes representing check equations. The bipartite graph of the code defined by  $H$  may be defined by  $N$  variable nodes and  $M$  check nodes. Every variable node of the  $N$  variable nodes has exactly  $d_v$  edges connecting this node to one or more of the check nodes (within the check  $M$  nodes). This number of  $d_v$  edges may be referred to as the degree of a variable node. Analogously, every check node of the  $M$  check nodes has exactly  $d_c$  edges connecting this node to one or more of the variable nodes. This number of  $d_c$  edges may be referred to as the degree of a check node.

An edge between a variable node  $v_i$  and check node  $c_j$  may be defined by  $e = (i, j)$ . However, on the other hand, given an edge  $e = (i, j)$ , the nodes of the edge may alternatively be denoted as by  $e = (v(e), c(e))$ . Given a variable node  $v_i$ , one may define the set of edges emitting from the node  $v_i$  by  $E_v(i) = \{e | v(e) = i\}$ . Given a check node  $c_j$ , one may define the set of edges emitting from the node  $c_j$  by  $E_c(j) = \{e | c(e) = j\}$ . Continuing on, the derivative result will be  $|E_v(i)| = d_v$  and  $|E_c(j)| = d_c$ .

An irregular LDPC code may also described using a bipartite graph. However, the degree of each set of nodes within an irregular LDPC code may be chosen according to some distribution. Therefore, for two different variable nodes,  $v_{i_1}$  and  $v_{i_2}$ , of an irregular LDPC code,  $|E_v(i_1)|$  may not equal to  $|E_v(i_2)|$ . This relationship may also hold true for two check nodes. The concept of irregular LDPC codes was originally introduced within M. Luby, M. Mitzenmacher, A. Shokrollahi, D. Spielman and V. Stemann, "Practical loss-resilient codes," *IEEE Trans. Inform. Theory*, Vol. 47, pp. 569-584, Feb. 2001.

In general, with a graph of an LDPC code, the parameters of an LDPC code can be defined by a degree of distribution, as described within M. Luby, *et al.* (referenced

above) and also within T. J. Richardson and R. L. Urbanke, "The capacity of low-density parity-check code under message-passing decoding," *IEEE Trans. Inform. Theory*, Vol. 47, pp. 599-618, Feb. 2001. This distribution may be described as follows:

- 5           Let  $\lambda_i$  represent the fraction of edges emanating from variable nodes of degree  $i$  and let  $\rho_i$  represent the fraction of edges emanating from check nodes of degree  $i$ . Then, a degree distribution pair  $(\lambda, \rho)$  is defined as follows:

$$\lambda(x) = \sum_{i=2}^{M_v} \lambda_i x^{i-1} \text{ and } \rho(x) = \sum_{i=2}^{M_c} \rho_i x^{i-1}, \text{ where } M_v \text{ and } M_c \text{ represent the maximal}$$

degrees for variable nodes and check nodes, respectively.

- 10           From certain perspectives, the invention may be implemented within communication systems that involve combining modulation coding with LDPC coding to generate LDPC coded signals. These LDPC coded signals may be such that they have a code rate and/or modulation (constellation and mapping) that varies as frequently as on a symbol by symbol basis. Up to now, there have been some attempts  
15           to combine modulation encoding with LDPC coding, yet they are all limited to employing only a single code rate or modulation (constellation and mapping) symbols generated thereby. Nevertheless, some of the possible approaches to combine modulation coding and LDPC coding are described below.

- FIG. 15A is a diagram illustrating an embodiment of direct combining of LDPC  
20           (Low Density Parity Check) coding and modulation encoding. A binary sequence (e.g., a bit stream) is provided to an LDPC (Low Density Parity Check) encoder. The LDPC encoder introduces a degree of redundancy (or parity) within the bit sequence provided thereto. These LDPC coded bits are then provided to a S/P (Serial to Parallel) path such that the output symbols may be provided to a modulation encoder.  
25           This S/P path performs the bit to m-bit symbol transformation. The modulation encoder outputs a signal sequence that includes symbols (composed of LDPC coded bits) that correspond to a modulation having a constellation and a mapping.

- FIG. 15B is a diagram illustrating an embodiment of BICM (Bit Interleaved Coded Modulation) that is employed in conjunction with LDPC (Low Density Parity  
30           Check) coding and modulation encoding. This embodiment is similar to the

embodiment described above that performs direct combining of LDPC coding and modulation encoding, with the exception that an interleaver is interposed between the LDPC encoder and the modulation encoder.

5 A binary sequence (e.g., a bit stream) is provided to an LDPC encoder. The LDPC encoder introduces a degree of redundancy (or parity) within the bit sequence provided thereto. These LDPC coded bits are then provided to an interleaver to generate a degree of randomness within the LDPC coded bits thereby (hopefully) making that LDPC coded bit sequence to be more robust to interference, noise, and other deleterious effects. This LDPC coded bit sequence that has been interleaved is  
10 then provided to a S/P (Serial to Parallel) path such that the output symbols may be provided to a modulation encoder. Again, this S/P path performs the bit to m-bit symbol transformation. The modulation encoder outputs a signal sequence that includes symbols (composed of the interleaved LDPC coded bits) that correspond to a modulation having a constellation and a mapping.

15 FIG. 15C is a diagram illustrating an embodiment of multilevel coded modulation encoding. Rather than require a S/P (Serial to Parallel) path between a single LDPC encoder and a modulation encoder, this embodiment shows a plurality of LDPC encoders operating in parallel such that the outputs of each of the LDPC encoder is already within parallel format (thereby obviating the need for the S/P  
20 (Serial to Parallel) path employed within the embodiments described above). The outputs of these LDPC encoders are provided to a modulation encoder. The modulation encoder outputs a signal sequence that includes symbols (composed of the LDPC coded bits provided by the various LDPC encoders) that correspond to a modulation having a constellation and a mapping.

25 All 3 of these embodiments, described above that perform the combination of LDPC coding and modulation encoding, typically operate using a single code rate and also use a single modulation (constellation and mapping) to map the binary bits to a given constellation. That is to say, they all typically employ a single code rate and a single modulation (having a single constellation type and a single mapping) for that  
30 single constellation. This approach inherently limits the maximal performance that may be achieved using these approaches. In contradistinction, the invention is

operable to operate on LDPC coded signals having a code rate and/or a modulation (constellation and mapping) that may vary as frequently as on a symbol by symbol basis. To illustrate further the single modulation approach of these 3 embodiments, a specific implementation that performs such a single mapping is described below.

5           FIG. 18 is a diagram illustrating an embodiment of a variable signal mapping LDPC (Low Density Parity Check) coded modulation system that is built in accordance with invention. This embodiment shows how a general implementation may be made for mapping an LDPC block coded modulation signal thereby generating LDPC coded signals having a modulation (constellation and mapping) that may vary  
10 as frequently as on a symbol by symbol basis.

In general, for any modulation, one can select as many as possible constellations and corresponding mappings, to construct an LDPC coded signal having a modulation (constellation and mapping) that may vary as frequently as on a symbol by symbol basis. This diagram illustrates a possible implementation for an m-bit  
15 constellation modulation. Moreover, it is also noted that the code can be any one of a variety of block codes.

In a very general illustration, a plurality of different encoders is employed. A first encoder employs a part 1 of a codeword, a second encoder employs a part 2 of a codeword, ..., and a final encoder (of the plurality of encoders) employs a part m of a  
20 codeword. Those symbols that satisfy a condition 1 are provided to a map I1. Similarly, those symbols that satisfy a condition 2 are provided to a map I2, and those symbols that satisfy a condition N are provided to a map IN. The various conditions employed to govern the direction of which mapping to which the symbols are provided may be selected by a designer implementing the invention.

25           The signal sequence generated by this embodiment, or any of the other embodiments for which the decoding approaches of the invention may operate, may be a variable code rate and/or a variable modulation signal. For example, the code rate of the symbols of the signal sequence may vary as frequently as on a symbol by symbol basis. A first symbol may be encoded according to a first code rate, and a second  
30 symbol may be encoded according to a second code rate.



In addition, the modulation of the symbols of the signal sequence may vary as frequently as on a symbol by symbol basis. More specifically, for the variable modulation type signal, either one or both of the constellation or mapping of the symbols of the signal sequence may vary as frequently as on a symbol by symbol basis. As yet another example, multiple symbols of the signal sequence may all be mapped to a similarly shaped constellation, yet various symbols may also have different mappings to the same constellation. As one specific example, two symbols may each be associated with an 8 PSK (8 Phase Shift Key) shaped constellation, yet each of the symbols may be mapped differently within that 8 PSK shaped constellation. Clearly, other types of modulations may also be employed without departing from the scope and spirit of the invention.

FIG. 19 is a diagram illustrating an embodiment of LDPC (Low Density Parity Check) coded modulation decoding functionality using bit metric according to the invention. To perform decoding of an LDPC coded modulation signal having an m-bit signal sequence, the functionality of this diagram may be employed. After receiving the I,Q (In-phase, Quadrature) values of a signal at the symbol nodes, an m-bit symbol metric computer functional block calculates the corresponding symbol metrics. At the symbol nodes, these symbol metrics are then passed to a symbol node calculator functional block that uses these received symbol metrics to calculate the bit metrics corresponding to those symbols. These bit metrics are then passed to the bit nodes connected to the symbol nodes.

Thereafter, at the bit nodes, a bit node calculator functional block operates to compute the corresponding soft messages of the bits. Then, in accordance with iterative decoding processing, the bit node calculator functional block receives the edge messages from a check node operator functional block and updates the edge messages with the bit metrics received from the symbol node calculator functional block. These edge messages, after being updated, are then passed to the check node operator functional block.

At the check nodes, the check node operator functional block then receives these edge messages sent from the bit nodes (from the bit node calculator functional block) and updates them accordingly. These updated edge messages are then passed

back to the bit nodes (e.g., to the bit node calculator functional block) where the soft information of the bits is calculated using the bit metrics and the current iteration values of the edge messages. Thereafter, using this just calculated soft information of the bits (shown as the soft message), the bit node calculator functional block updates  
5 the edge messages using the previous values of the edge messages (from the just previous iteration) and the just calculated soft message. The iterative processing continues between the bit nodes and the check nodes according to the LDPC code bipartite graph that was employed to encode the signal that is being decoded.

These iterative decoding processing steps, performed by the bit node calculator  
10 functional block and the check node operator functional block, are repeated a predetermined number of iterations (e.g., repeated  $n$  times, where  $n$  is selectable). Alternatively, these iterative decoding processing steps are repeated until the syndromes of the LDPC code are all equal to zero (within a certain degree of precision).

15 Soft output information is generated within the bit node calculator functional block during each of the decoding iterations. In this embodiment, this soft output may be provided to a hard limiter where hard decisions may be made, and that hard information may be provided to a syndrome calculator to determine whether the syndromes of the LDPC code are all equal to zero (within a certain degree of  
20 precision). When they are not, the iterative decoding processing continues again by appropriately updating and passing the edge messages between the bit node calculator functional block and the check node operator functional block.

After all of these iterative decoding processing steps have been performed, then the best estimates of the bits are output based on the bit soft information. In the  
25 approach of this embodiment, the bit metric values that are calculated by the symbol node calculator functional block are fixed values and used repeatedly in updating the bit node values.

FIG. 20 is a diagram illustrating an alternative embodiment of LDPC coded modulation decoding functionality using bit metric according to the invention (when  
30 performing  $n$  number of iterations). This embodiment shows how the iterative decoding processing may be performed when a predetermined number of decoding

iterations, shown as  $n$ , is performed. If the number of decoding iterations is known beforehand, as in a predetermined number of decoding iterations embodiment, then the bit node calculator functional block may perform the updating of its corresponding edge messages using the bit metrics themselves (and not the soft information of the bits as shown in the previous embodiment and described above). This processing may be performed in all but the last decoding iteration (e.g., for iterations 1 through  $n-1$ ). However, during the last iteration, the bit node calculator functional block calculated the soft information of the bits (shown as soft output). The soft output is then provided to a hard limiter where hard decisions may be made of the bits. The syndromes need not be calculated in this embodiment since only a predetermined number of decoding iterations are being performed.

FIG. 21 is a diagram illustrating an alternative embodiment of LDPC (Low Density Parity Check) coded modulation decoding functionality using bit metric (with bit metric updating) according to the invention. To perform decoding of an LDPC coded modulation signal having an  $m$ -bit signal sequence, the functionality of this diagram may be employed. After receiving the I,Q (In-phase, Quadrature) values of a signal at the symbol nodes, an  $m$ -bit symbol metric computer functional block calculates the corresponding symbol metrics. At the symbol nodes, these symbol metrics are then passed to a symbol node calculator functional block that uses these received symbol metrics to calculate the bit metrics corresponding to those symbols. These bit metrics are then passed to the bit nodes connected to the symbol nodes. The symbol node calculator functional block is also operable to perform bit metric updating during subsequent decoding iterations.

Thereafter, at the bit nodes, a bit node calculator functional block operates to compute the corresponding soft messages of the bits. Then, in accordance with iterative decoding processing, the bit node calculator functional block receives the edge messages from a check node operator functional block and updates the edge messages with the bit metrics received from the symbol node calculator functional block. This updating of the edge messages may be performed using the updated bit metrics during subsequent iterations. These edge messages, after being updated, are then passed to the check node operator functional block.

At the check nodes, the check node operator functional block then receives these edge messages sent from the bit nodes (from the bit node calculator functional block) and updates them accordingly. These updated edge messages are then passed back to the bit nodes (e.g., to the bit node calculator functional block) where the soft information of the bits is calculated using the bit metrics and the current iteration values of the edge messages. Thereafter, using this just calculated soft information of the bits (shown as the soft message), the bit node calculator functional block updates the edge messages using the previous values of the edge messages (from the just previous iteration) and the just calculated soft message. At the same time, as the just calculated soft information of the bits (shown as the soft message) has been calculated, this information may be passed back to the symbol nodes (e.g., to the symbol node calculator functional block) for updating of the bit metrics employed within subsequent decoding iterations. The iterative processing continues between the bit nodes and the check nodes according to the LDPC code bipartite graph that was employed to encode the signal that is being decoded (by also employing the updated bit metrics during subsequent decoding iterations).

These iterative decoding processing steps, performed by the bit node calculator functional block and the check node operator functional block, are repeated a predetermined number of iterations (e.g., repeated  $n$  times, where  $n$  is selectable). Alternatively, these iterative decoding processing steps are repeated until the syndromes of the LDPC code are all equal to zero (within a certain degree of precision).

Soft output information is generated within the bit node calculator functional block during each of the decoding iterations. In this embodiment, this soft output may be provided to a hard limiter where hard decisions may be made, and that hard information may be provided to a syndrome calculator to determine whether the syndromes of the LDPC code are all equal to zero (within a certain degree of precision). When they are not, the iterative decoding processing continues again by appropriately updating and passing the edge messages between the bit node calculator functional block and the check node operator functional block.

After all of these iterative decoding processing steps have been performed, then the best estimates of the bits are output based on the bit soft information. In the approach of this embodiment, the bit metric values that are calculated by the symbol node calculator functional block are fixed values and used repeatedly in updating the bit node values.

FIG. 22 is a diagram illustrating an alternative embodiment of LDPC coded modulation decoding functionality using bit metric (with bit metric updating) according to the invention (when performing  $n$  number of iterations). This embodiment shows how the iterative decoding processing may be performed when a predetermined number of decoding iterations, shown as  $n$ , is performed (again, when employing bit metric updating). If the number of decoding iterations is known beforehand, as in a predetermined number of decoding iterations embodiment, then the bit node calculator functional block may perform the updating of its corresponding edge messages using the bit metrics/updated bit metrics themselves (and not the soft information of the bits as shown in the previous embodiment and described above). This processing may be performed in all but the last decoding iteration (e.g., for iterations 1 through  $n-1$ ). However, during the last iteration, the bit node calculator functional block calculated the soft information of the bits (shown as soft output). The soft output is then provided to a hard limiter where hard decisions may be made of the bits. The syndromes need not be calculated in this embodiment since only a predetermined number of decoding iterations are being performed.

FIG. 23A is a diagram illustrating bit decoding using bit metric (shown with respect to an LDPC (Low Density Parity Check) code bipartite graph) according to the invention. Generally speaking, after receiving I, Q values of a signal at a symbol nodes, the  $m$ -bit symbol metrics are computed. Then, at the symbol nodes, the symbol metric is used to calculate the bit metric. The bit metric is then passed to the bit nodes connected to the symbol nodes. At the bit nodes, the soft messages of the bits are computed, and they are used to update the edge message sent from the check nodes with the bit metric. These edge messages are then passed to the check nodes. At the check nodes, updating of the edge messages sent from the bit nodes is performed, and these values are pass back the bit nodes.

As also described above with respect to the corresponding functionality embodiment, after all of these iterative decoding processing steps have been performed, then the best estimates of the bits are output based on the bit soft information. In the approach of this embodiment, the bit metric values that are  
5 calculated by the symbol node calculator functional block are fixed values and used repeatedly in updating the bit node values.

FIG. 23B is a diagram illustrating bit decoding using bit metric updating (shown with respect to an LDPC (Low Density Parity Check) code bipartite graph) according to the invention. With respect to this LDPC code bipartite graph that  
10 performs bit metric updating, the decoding processing may be performed as follows:

After receiving the I, Q value of the signal at the symbol nodes, the m-bit symbol metrics are computed. Then, at the symbol nodes, the symbol metrics are used to calculate the bit metrics. These values are then passed to the bit nodes connected to the symbol nodes. At the bit nodes, the edge message sent from the check nodes are  
15 updated with the bit metrics, and these edge messages are passed to the check nodes. In addition, at the same time the soft bit information is updated and passed back to the symbol nodes. At the symbol nodes, the bit metrics are updated with the soft bit information sent from the bit nodes, and these values are passed back to the variable nodes. At the check nodes, the edge information sent from the bit nodes is updated,  
20 and this information is passed back to the bit nodes.

As also described above with respect to the corresponding functionality embodiment, after all of these iterative decoding processing steps have been performed, then the best estimates of the bits are output based on the bit soft information. Again, it is shown in this embodiment that the bit metric values are not  
25 fixed; they are updated for use within subsequent decoding iterations. This is again in contradistinction to the embodiment described above where the bit metric values that are calculated only once and remain fixed values for all of the decoding iterations.

FIG. 24A is a diagram illustrating an LDPC (Low Density Parity Check) coded modulation tripartite graph with symbol nodes connected to bit nodes according to the  
30 invention. In this embodiment, it can be seen that the bit nodes are connected to the symbol nodes. The appropriately corresponding bit nodes are also connected to the

check nodes according to the LDPC code being employed. However, it is noted that the symbols to be decoded are solely determined by the bits connected to the corresponding symbol. This property is capitalized upon such that the bit nodes may be removed from the LDPC tripartite graph, so that the symbol nodes may be directly  
 5 connected to the check nodes thereby generating an LDPC coded modulation bipartite graph.

As one example, 3 symbol nodes,  $s_0, s_1, s_2$ , are connected to the 9 bit nodes,  $b_0, b_1, b_2, \dots, b_8$ , according to the following mapping:

$$\begin{aligned} s_0 &\leftrightarrow (b_0, b_3, b_6) \\ s_1 &\leftrightarrow (b_1, b_4, b_7) \\ s_2 &\leftrightarrow (b_2, b_5, b_8) \end{aligned} \quad (\text{EQ 1})$$

10 The connections between the 9 bit nodes,  $b_0, b_1, b_2, \dots, b_8$ , and the 3 check nodes,  $c_0, c_1, c_2$ , are made according to the following mapping:

$$\begin{aligned} b_0 &\leftrightarrow (c_0, c_2) \\ b_1 &\leftrightarrow (c_0, c_1) \\ b_2 &\leftrightarrow (c_1, c_2) \\ b_3 &\leftrightarrow (c_0, c_1) \\ b_4 &\leftrightarrow (c_1, c_2) \\ b_5 &\leftrightarrow (c_0, c_2) \\ b_6 &\leftrightarrow (c_0, c_1) \\ b_7 &\leftrightarrow (c_1, c_1) \\ b_8 &\leftrightarrow (c_0, c_1) \end{aligned}$$

FIG. 24B is a diagram illustrating an LDPC (Low Density Parity Check) coded modulation bipartite graph with symbol nodes connected directly to check nodes according to the invention (this bipartite graph is generated from the tripartite graph shown in FIG. 24A). One aspect of the invention is the ability to reduce the number of  
 15 nodes within an LDPC bipartite graph by directly connecting the symbols nodes to the check nodes (e.g., by modifying an LDPC coded modulation tripartite graph to generate an LDPC coded modulation bipartite graph). However, this must be  
 20 performed very carefully to ensure proper decoding of such LDPC coded signals. As

is described herein, the labeling of the edges connected the symbols nodes to the check nodes needs to be done carefully to ensure proper decoding of symbols.

Within this LDPC code bipartite graph, the edges are only connected between the symbol nodes and the check nodes. In doing so, every edge connecting the symbol nodes and the check nodes is labeled by a value according to EQ 1 shown above. In some embodiments, these edges are labeled using octal values.

For example, using an octal labeling approach, the edge connecting the symbol node  $s_0$  to the check node  $c_0$ , depicted as  $(s_0, c_0)$ , is labeled as 7 since all three bits  $b_0, b_3, b_6$  are connected to  $c_0$  (e.g., labeled as 7 because  $b_0, b_3, b_6 = 111$ ). Similarly, the edge connecting the symbol node  $s_0$  to the check node  $c_1$ , depicted as  $(s_0, c_1)$ , is labeled as 6 since only the two bits  $b_0, b_3$  are connected to  $c_1$  (e.g., labeled as 6 because  $b_0, b_3, b_6 = 110$ ). As another example, the edge connecting the symbol node  $s_0$  to the check node  $c_2$ , depicted as  $(s_0, c_2)$ , is labeled as 1 since only the one bit  $b_0$  is connected to  $c_2$  (e.g., labeled as 1 because  $b_0, b_3, b_6 = 100$ ). The additional edges that communicatively couple the symbols nodes to the check nodes may also be labeled according to this convention.

One of the advantages of the symbol node to check node LDPC code bipartite graph is that a decoder may use symbol metrics when performing the decoding processing of the LDPC coded symbols instead of bit metrics. In this way of performing the decoding processing, there is therefore no need to perform metric updating; the metric updating within the decoding processing may have the undesirable effect of requiring an increased amount of memory to be used. Moreover, the decoding based on the LDPC code bipartite graph (sometimes referred to as a symbol LDPC code bipartite graph) actually out-performs decoding processing that is based on an LDPC code tripartite graph (whose bit nodes are connected to check nodes). In addition, the LDPC symbol decoding provides comparable or better performance of LDPC bit decoding that involves updating of the bit metrics.

FIG. 25A is a diagram illustrating symbol decoding (shown with respect to an LDPC (Low Density Parity Check) coded modulation bipartite graph) according to the invention. The symbol decoding processing performed according to the invention may



be performed using an LDPC coded modulation bipartite graph in which the symbol nodes are connected directly to the check nodes. In general, the I,Q values of a symbol are provided to the symbol nodes, and the iterative decoding processing is performed according to the manner in which the labeled edges communicatively  
 5 couple the symbol nodes to the check nodes.

As an example of how the decoding processing may be performed using such an LDPC coded modulation bipartite graph, a rate 2/3 LDPC code with an 8 PSK (8 Phase Shift Key) modulation signal is decoded and explained in detail. This LDPC code may be a regular LDPC code or an irregular LDPC code without departing from  
 10 the scope and spirit of the invention. The block length of the LDPC code is  $3N$  and a 3 bit symbol  $s_i$  is mapped (e.g., using a symbol mapper) according to the following notation:

$$s_i = (b_i, b_{N+i}, b_{2N+i})$$

The parity check matrix of the LDPC code may be represented as  $[h_{ij}]_{N \times 3N}$ .  
 15 The estimated symbols  $r_i$  corresponding to the 3 bit symbol  $s_i$  may be represented as  $r_i = (r_{0i}, r_{1i}, r_{2i})$ . The partial syndromes  $S^m(i)$  and  $S_m(i)$  that are calculated using the estimated symbols and the parity check matrix of the LDPC code may be represented as follows:

$$\begin{aligned} S^m(i) &= \sum_{j=0}^{m-1} (r_{0j} h_{ij} + r_{1j} h_{i(N+j)} + r_{2j} h_{i(2N+j)}) \\ S_m(i) &= \sum_{j=m}^{N-1} (r_{0j} h_{ij} + r_{1j} h_{i(N+j)} + r_{2j} h_{i(2N+j)}) \end{aligned} \quad (\text{EQ 2})$$

20 The following decoding processing description is described as being performed on a signal sequence  $Y$ . The probability of the signal sequence  $Y$  satisfying the partial syndrome,  $p(S^j(i) = m | Y)$ , to be equal to  $A_{i,j}(m)$  is calculated (e.g., the probability of  $p(S^j(i) = m | Y) = A_{i,j}(m)$ ). In addition, other probabilities are calculated; namely, the probability of the signal sequence  $Y$  satisfying the partial syndrome,  $p(S_j(i) = m | Y)$ ,  
 25 to be equal to  $B_{i,j}(m)$  is calculated (e.g., the probability of  $p(S_j(i) = m | Y) = B_{i,j}(m)$ ). These probabilities are all calculated based on the following conditions:

$$\begin{aligned}
A_{i,0}(0) &= 1 \\
B_{i,\deg(c_i)-1}(0) &= 1, \text{ and} \\
A_{i,0}(m) &= 0 \\
B_{i,\deg(c_i)-1}(m) &= 0, \text{ where } m \neq 0.
\end{aligned}$$

Since the decoding may be performed in the logarithmic domain thereby enabling multiplication operations to be performed using addition and division operations to be performed using subtraction, these variables may be redefined within the logarithmic domain as follows:

$$\begin{aligned}
\alpha_{i,j}(m) &= \log(A_{i,j}(m)) \\
\beta_{i,j}(m) &= \log(B_{i,j}(m))
\end{aligned}$$

These values may be referred to as the alphas, or forward metrics,  $(\alpha_{i,j}(m))$  and betas, or backward metrics,  $(\beta_{i,j}(m))$  to be employed within the decoding processing.

The edge messages being passed from the check nodes to the symbol nodes may be represented as  $Medge[i][j][k]$ , where  $i$  runs according to the appropriately labeled edges within the LDPC coded modulation bipartite graph.

As some examples:

1. if the label is 7, then  $k$  runs from 0 to 7,
2. if the label is 3, 5, or 6, then  $k$  runs from 0 to 3, and
3. if the label is 1, 2, or 6, then  $k$  runs between 0 to 1.

In addition, a new function  $x(\nu)$  that varies from  $\{0, \dots, 7\}$  to  $\{0, 1\}$  may be employed. The value  $\nu$  may be viewed as being an integer represented in octal. Then, the value of  $\nu$  may be represented as  $\nu = (\nu_0, \nu_1, \nu_2)$ . This new function  $x(\nu)$  may be represented as follows:

$$x(\nu) = \nu_0 \oplus \nu_1 \oplus \nu_2 \quad (\text{EQ 3})$$

where  $\oplus$  is an exclusive-or function (e.g., binary addition).

The notation and definitions provided above are also employed to describe the symbol decoding processing in other embodiments whose decoding processing and/or functionality are described in more detail below. More specifically, the embodiments described in more detail below show how the check node updating and symbol

sequence estimation, as well as symbol node updating, is performed using these various values.

FIG. 25B is a diagram illustrating an embodiment of symbol decoding functionality (supported with an LDPC (Low Density Parity Check) coded modulation bipartite graph) according to the invention. This embodiment shows in more detail how the check node updating and symbol sequence estimation, as well as symbol node updating, is performed.

The decoding processing described in this embodiment may be better understood in the context of the check node updating and symbol sequence estimation, including the symbol node updating, that may be performed within in at least 2 different embodiments that are described herein in accordance with the invention: (1) symbol decoding and (2) hybrid decoding (that performs a combination of bit level and symbol level decoding). One possible embodiment of symbol decoding is described in this diagram (FIG. 25B), and one possible embodiment of the hybrid decoding is described below with respect to the diagram of FIG. 27.

Beginning from the left hand side of the diagram, input information corresponding to the calculated partial syndromes, that also includes the initial values of the alphas  $(\alpha_{i,j}(m))$  and the betas  $(\beta_{i,j}(m))$  (e.g., forward and backward metrics), are provided to a check node update functional block. Iterative decoding processing is performed within the check node update functional block over the total number of check nodes. For example,  $M$  iterations are performed over  $i$  (where  $i$  varies from 0 to  $M-1$ , and where  $M$  is the total number of check nodes of the LDPC bipartite graph).

In doing this iterative decoding processing, the check node updating initially involves calculating the values of the alphas  $(\alpha_{i,j}(m))$  and the betas  $(\beta_{i,j}(m))$  (beyond merely the initial values that are provided during the initial iteration) for each of the symbols of a received symbol block. This iterative decoding processing in calculating the alphas and betas may be performed using a forward-backward procedure through the received symbol block.

The calculation of the alphas and betas is described below.

For  $j = 0$  to  $\deg(c_i) - 1$  and  $m = 0, 1$ , the forward-backward processing procedure may be employed to calculate the alphas  $(\alpha_{i,j}(m))$  and the betas  $(\beta_{i,j}(m))$  as follows:

$$\begin{aligned} \alpha_{i,j}(m) &= \min^* \{ \text{Medge}[i][j-1][k] + \alpha_{i,j-1}(m \oplus x(k)) \mid \text{all possible } k \} \\ \beta_{i,j}(m) &= \min^* \{ \text{Medge}[i][j+1][k] + \beta_{i,j+1}(m \oplus x(k)) \mid \text{all possible } k \} \end{aligned}$$

Now that these values of alpha and beta are available for each of the symbols within a received symbol block, the edge messages  $\text{Medge}[i][j][k]$  (that communicatively couple the symbol nodes to the check nodes) are updated using these calculated alphas and betas values.

For  $j = 0$  to  $\deg(c_i) - 1$  and all possible  $k$ , the updating of the edge messages  $\text{Medge}[i][j][k]$  may be performed as follows:

$$\text{Medge}[i][j][k] = \min^* \{ \alpha_{i,j}(0) + \beta_{i,j}(x(k)), \alpha_{i,j}(1) + \beta_{i,j}(x(k) \oplus 1) \}$$

The  $\min^*$  processing functionality described herein may be better understood by the following description. The  $\min^*$  processing includes determining a minimum value from among two values (e.g., shown as  $\min(A, B)$  in  $\min^*$  processing) as well as determining a logarithmic correction factor (e.g., shown as  $\ln(1 + e^{-|A-B|})$  in  $\min^*$  processing) in selecting the smaller metric. In addition, it is also noted that  $\max^*$  processing may alternatively be performed in place of  $\min^*$  processing. The  $\max^*$  processing operation also includes a logarithmic correction in selecting the larger metric. It is noted that the various embodiments of the invention may be implemented using the  $\max^*$  operations in lieu of the  $\min^*$  operation when preferred in a given implementation.

The  $\min^*$  processing, when operating on inputs  $A$  and  $B$ , may be expressed as follows:

$$\min^*(A, B) = \min(A, B) - \ln(1 + e^{-|A-B|})$$

Again, the  $\min^*$  processing may alternatively be performed using  $\max^*$  processing. The  $\max^*$  processing, when operating on inputs  $A$  and  $B$ , may be expressed as follows:

$$\max^*(A, B) = \max(A, B) + \ln(1 + e^{-|A-B|})$$

Moreover, when multiple min\* operations are to be performed on multiple values (e.g., more than 2), the min\* processing may be expressed as follows:

$$\min^*(x_1, \dots, x_N) = \min^*(\min^*(x_1, \dots, x_{N-1}), x_N) \quad (\text{EQ 4})$$

- 5 After the check node processing has been completed, a symbol sequence estimate and symbol node update functional block operates using the check node update messages to continue the decoding processing.

Since the total number of edges is the same count from either side (e.g., from either the symbol node side or the check node side), the edges are intrinsically re-ordered according to the symbols that are being decoded. This re-ordering may be intrinsically performed using a LUT (Look-Up Table) to ensure the proper ordering of the check node updating. In other words, the LUT may be implemented to perform the function of which edge information to take when performing the symbol sequence estimate and symbol node update. In addition, this re-ordering functionality may be inherently implemented in hardware for proper ordering of the check node updating such that it corresponds to an order that is appropriate to the symbol node updating. For proper decoding of the symbols of the sequence (e.g., first symbol to last symbol), there needs to be some ordering of the symbols. However, this symbol ordering is not critical when performing the check node updating. That is to say, the ordering of the check node updating may then be performed according to any desired ordering, and to ensure proper decoding of the symbols according to the desired order (e.g., first symbol to last symbol), the check node updating is performed to ensure that the edge messages are inherently appropriately ordered according to the desired order for the decoding processing.

- 25 More specifically, this decoding processing may be understood with respect to the edge messages  $\text{Medge}[i][j][k]$ , where  $i$  runs across all of the symbol nodes, where  $j$  runs according to the degree of the edges from the symbol nodes, and where  $k$  runs according to the labels of the LDPC bipartite graph.

This embodiment described with respect to this diagram is shown with respect to a code that includes 3 bit symbols, coded according to 8 PSK (8 Phase Shift Key)

modulation. However, it is noted that such a decoding approach may also be adapted very easily to decoding signals having an even larger number of bits. For example, this decoding approach may be adapted to perform decoding of signals having symbols of higher order modulations including 16 QAM (16 Quadrature Amplitude Modulation), 16 APSK (16 Asymmetric Phase Shift Keying), 64 QAM, and even other modulation types without departing from the scope and spirit of the invention.

The label on the  $j$ -th edge from the check node  $i$  may be denoted as  $L_{i,j}$ . A new function,  $sh(L, \nu)$ , may be defined and employed to assist in the decoding processing describer herein. This new function  $sh(L, \nu)$  may be defined as follows:

$$sh(L, (\nu_0, \nu_1, \nu_2)) = \begin{cases} \nu_2 & L = 1 \\ \nu_1 & L = 2 \\ (\nu_1, \nu_2) & L = 2 \\ \nu_0 & L = 4 \\ (\nu_0, \nu_2) & L = 5 \\ (\nu_0, \nu_1) & L = 6 \\ (\nu_0, \nu_1, \nu_2) & L = 7 \end{cases} \quad (\text{EQ } 5)$$

After the edge messages have been intrinsically and appropriately re-ordered using the approach described above, the symbol sequence estimate and symbol node update functional block continues to operate according to the following procedure.

For  $m = 0, \dots, 7$ , the possible values for the soft symbol estimates are computed (e.g., the possible values for the soft information of the symbols is calculated) as follows:

$$p_i(m) = Metric_i[m] + \sum_{j=0}^{\deg(s_i)-1} \left( \sum_{L_{i,j}} Medge[i] \mathbf{I}_j[sh(L_{i,j}, m)] \right), \text{ where } Metric_i[m] \text{ is the}$$

appropriate symbol metric obtained from the received signal according to its appropriate modulation (constellation and mapping values).

The symbol sequence estimate and symbol node update functional block continues by estimating the symbols using the soft symbol estimates. More specifically, the estimate of the symbol  $s_i$  to  $m$  is made such that  $p_i(m)$  is the smallest value selected from among all of the possible values of  $p_i(0), p_i(1), \dots, p_i(7)$ .

After the estimate of the symbols is made using the soft symbol estimates, the edge messages are updated within the symbol sequence estimate and symbol node update functional block using the older edge messages. More specifically, the edge message are updated as follows:

- 5           The processing may be better understood by considering the edge label  $L_{i,j}$ ,
1.       if  $L_{i,j} = 7$  , then for  $m = 0, \dots, 7$  ,  $Medge[i][j][k] = p_i[m] - Medge[i][j][m]$ .
  2.       alternatively, if  $L_{i,j} = 3, 5, 6$  , then for  $m_0, m_1 \in \{0, 1\}$ , then the values of

the edge messages may be defined as:

$$Medge[i][j](m_0, m_1) = \begin{cases} \min^*(p_i(0, m_0, m_1), p_i(1, m_0, m_1)) - Medge[i][j](m_0, m_1) & L_{i,j} = 3 \\ \min^*(p_i(m_0, 0, m_1), p_i(m_0, 1, m_1)) - Medge[i][j](m_0, m_1) & L_{i,j} = 5 \\ \min^*(p_i(m_0, m_1, 0), p_i(m_0, m_1, 1)) - Medge[i][j](m_0, m_1) & L_{i,j} = 6 \end{cases}$$

- 10           3.       alternatively, if  $L_{i,j} = 1, 2, 4$  , then for  $m = 0, 1$ , then the values of the edge messages may be defined as:

$$Medge[i][j](m) = \begin{cases} \min^*\{p_i(k_0, k_1, m) | k_0, k_1 \in \{0, 1\}\} - Medge[i][j][m] & L_{i,j} = 1 \\ \min^*\{p_i(k_0, m, k_1) | k_0, k_1 \in \{0, 1\}\} - Medge[i][j][m] & L_{i,j} = 2 \\ \min^*\{p_i(m, k_0, k_1) | k_0, k_1 \in \{0, 1\}\} - Medge[i][j][m] & L_{i,j} = 4 \end{cases}$$

where the right hand side edge of these equations is the old edge message passed from the check node.

- 15           Continuing on with the iterative decoding processing, using the updated edge messages (that are updated either a predetermined number of times and/or until convergence of the edge messages has been met within a certain degree of precision), then the best estimates of the symbols of a received symbol block may be made.

- 20           The performance of various approaches to decoding such a received symbol block are compared in the following diagram.

FIG. 26 is a diagram illustrating an embodiment of performance comparison of symbol vs. bit decoding of LDPC (Low Density Parity Check) code modulation signals according to the invention. These performance curves are described in the context of BER (Bit Error Rate) versus  $E_b/N_0$  (ratio of energy per bit  $E_b$  to the Spectral Noise

Density  $N_0$ ). This term  $E_b/N_0$  is the measure of SNR (Signal to Noise Ratio) for a digital communication system. When looking at these performance curves, the BER may be determined for any given  $E_b/N_0$  (or SNR).

Three different decoding approaches are compared when decoding LDPC coded modulation signals. Within this comparison, the block size of the LDPC code is 14400, and the signal is a code rate 2/3 8 PSK (8 Phase Shift Key) LDPC coded modulation signal.

As some example, the worst performing performance curve corresponds to bit decoding only; when operating at an  $E_b/N_0$  of approximately 3.5 dB (decibels), the BER of the bit decoding only approach is approximately  $2.5 \times 10^{-6}$ .

The next better performance curve corresponds to performing bit decoding in accompany with bit metric updating; for this decoding approach, when operating at an  $E_b/N_0$  of approximately 3.5 dB, the BER of the bit decoding approach (that also included metric updating) decreases even more to below approximately under  $2 \times 10^{-7}$ .

However, the symbol decoding approach described herein provides a better performance than either of these other approaches. More specifically, for this symbol decoding approach performed in accordance with the invention, when operating at an  $E_b/N_0$  of approximately 3.5 dB, the BER of the symbol decoding approach decreases by an even greater amount to approximately  $1 \times 10^{-7}$ .

As can be seen when comparing these various approaches to performing decoding of LDPC coded modulation signals, the symbol decoding approach may be implemented as to provide for much improved performance.

FIG. 27 is a diagram illustrating an embodiment of hybrid decoding functionality that reduces the complexity of symbol decoding of LDPC coded modulation signals according to the invention.

This hybrid approach to performing decoding of LDPC coded modulation signals is similar to the symbol decoding approach described above within other embodiments with the exception being that the check nodes are updated using the edge messages corresponding to the bit nodes and the symbol nodes are updated using the symbol metrics and the combined edge messages corresponding to the bit nodes.



With respect to the LDPC code bipartite graphs described above, it is noted that the labels of some of the edges correspond to more than 1 bit. For example, for the bits 3, 5, 6, and 7, the edge messages correspond to more than 2 values. Because of this, the common approach of employing LLR (log likelihood ratio) decoding cannot  
5 be employed. Moreover, additional memory may be required to store the increased number of edge messages that are employed when performing symbol decoding.

The hybrid approach to LDPC coded modulation decoding may be employed to reduce the increase of complexity that may be associated with some implementations of symbol decoding of LDPC coded modulation signals.

10 The hybrid decoding approach may be characterized as follows:

1. updating the check nodes using the bit edge messages, and
2. updating the symbol nodes using the symbol metrics and the combined  
bit edge message.

Within this diagram, a modified check node update functional block and a  
15 symbol sequence estimate and symbol node update functional block are employed; these functional blocks (for the hybrid decoding functionality) are modified with respect to the symbol decoding functionality described above. This diagram is shown as receiving input that includes the partial syndrome information.

A check node update functional block performs updating of the edge messages  
20 therein. Initially, during a first decoding iteration, the check node update functional block calculates the edge messages for this first decoding iteration. These edge messages are then passed to a symbol sequence estimate and symbol node update functional block.

Within the symbol sequence estimate and symbol node update functional block  
25 and similar to the embodiment described above, since the total number of edges is the same count from either side (e.g., from either the symbol node side or the check node side), the edges are inherently ordered in a manner that is appropriate for the decoding. As also described above, this appropriate ordering may be implemented according to a LUT, or it may be inherently implemented in hardware. Again, the ordering of the  
30 decoded signal is what is important; the order in which the check nodes are processed

is not critical (they may be processed in an order that corresponds to the order in which the signal is to be decoded).

The symbol sequence estimate and symbol node update functional block continues by computing soft symbol estimates and by estimating the symbols using those calculated soft symbol estimates. Within the symbol sequence estimate and symbol node update functional block, after obtaining the soft symbol estimate  $p_i[m]$  from the symbol node update, min\* processing may be employed to decompose the soft symbol estimates to soft bit estimates for every edge (based on the labels of the edges). An example of this processing may be employed to understand the decoding processing by considering the  $j$ -th edge of the  $i$ -th symbol as having the label 5. This symbol then has 2 bits connected to the check node through this edge. The soft bit estimates for the  $k$ -th bit may be calculated as follows:

$$est_{i,j,0}[b] = \min^* \{p_i(m_0, m_1, b) \mid m_0, m_1 \in \{0,1\}\} \quad (\text{EQ 6})$$

$$est_{i,j,1}[b] = \min^* \{p_i(b, m_0, m_1) \mid m_0, m_1 \in \{0,1\}\}. \quad (\text{EQ 7})$$

The bit estimates are then made corresponding to these soft bit estimates. Using these soft bit estimates, the bit edge messages are then updated using the symbol metric and the combined bit edge messages. Once these bit edge messages are updated, they may then be passed to the check nodes to continue the subsequent iterations of the iterative decoding processing. Using this approach, memory can be reduced (when compared to the symbol decoding approach) and the LLR decoding approach may be performed in updating the check nodes.

Continuing on with the iterative decoding processing, the edge messages are then updated using the updated bit edge messages. The iterative decoding processing continues for a predetermined number of iterations or until the edge messages have converged to a solution within an acceptable degree of precision. Best estimates of the symbols of a received symbol block may then be made after the iterative decoding processing has been performed in a similar manner than in performed above with respect to the symbol decoding approach.

Some comments may be made when comparing the symbol decoding approach, the bit only decoding approach, the bit (with metric updating) decoding approach, and

the hybrid decoding approach. When updating of the symbol nodes is performed using symbol metrics, the edge messages for the symbols are needed. Therefore, the decoding processing has first to get back the edge message of the symbol from the edge message of the bits. Since the bit edge message is a probability of the bit related to the check node, then the conditional probability is needed to get the symbol probability. However, that probability is initially not available. Therefore, the decoding processing assumes that those bits are independent from one another. While this property does hold true for the information bits of the LDPC code, it is not necessarily true for the check bits. Because of this characteristic of the hybrid decoding approach, the hybrid decoding approach may incur some performance loss when compared to the other approaches of decoding described herein.

FIG. 28A is a flowchart illustrating an embodiment of a method for symbol decoding of LDPC coded modulation signals according to the invention. The method involves receiving a symbol block that includes a plurality of symbols. This symbol block may be viewed as being a block of LDPC coded modulation symbols. The symbols are then mapped according to an appropriate code rate and/or modulation. The modulation includes a constellation and a mapping for each symbol within the symbol block. Either one or both of the code rate and the modulation may vary within the symbol block as frequently as on a symbol by symbol basis.

Thereafter, the method continues by performing initial estimating of the symbols. The method then continues by performing check node updating. Thereafter, the method continues by performing symbol sequence estimating and symbol node updating. After the iterative decoding processing is completed, then the method finishes by outputting best estimates of the symbols of the received symbol block.

FIG. 28B is a flowchart illustrating an embodiment of a hybrid decoding method of LDPC coded modulation signals according to the invention. This hybrid method of decoding involves updating the check nodes using the bit edge message and also updating the symbol nodes using the symbol metric and combined bit edge message.

Many portions of this method may also include similar operational steps of the symbol decoding method described above. For example, the method may also involve

receiving a symbol block that includes a plurality of symbols. This symbol block may be viewed as being a block of LDPC coded modulation symbols. The symbols are then mapped according to an appropriate code rate and/or modulation. The modulation includes a constellation and a mapping for each symbol within the symbol block. Either one or both of the code rate and the modulation may vary within the symbol block as frequently as on a symbol by symbol basis.

This hybrid decoding method then involves obtaining soft symbol estimates from the symbol node updating. The method then involves decomposing the soft symbol estimates to soft bit estimates for every edge (based on the labeling of those edges).

The method then involves estimating the bits using the soft bit estimates. The bit edge messages are then updated using the symbol metric and the combined bit messages. The method then involves passing these updated edge messages to the check nodes. The method then involves updating the edge messages at the check nodes using the bit edge messages.

As with the symbol decoding method described above, the iterative decoding processing is also completed within this hybrid decoding method. The method then finishes by outputting best estimates of the symbols of the received symbol block.

It is also noted that the methods described within the preceding figures may also be performed within any of the appropriate system and/or apparatus designs (e.g., communication systems, communication devices, communication transceivers, communication receivers, and/or functionality described therein) that are described above without departing from the scope and spirit of the invention.

In view of the above detailed description of the invention and associated drawings, other modifications and variations will now become apparent. It should also be apparent that such other modifications and variations may be effected without departing from the spirit and scope of the invention.